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Detection of Lithium in a Main Sequence Bulge Star Using Keck I as a 15m Diameter Telescope

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ABSTRACT

The bulge contains the most chemically evolved old stellar population in the Milky Way. Thanks to microlensing, it is now possible to obtain high resolution echelle spectra of bulge stars near the main sequence turn-off, and study the abundance of elements that are affected by stellar evolution, such as lithium. We have observed with the HIRES spectrograph on the Keck I 10m telescope the source star of the MACHO microlensing event 97BLG45 while it was magnified by ~ 1 magnitude. Here we report the detection of the Li I line at $\lambda 6707.8$ Å in the echelle spectrum of this star, and measure the bulge lithium abundance for the first time: $A(Li) = 2.25 \pm 0.25$.

Subject headings: Galaxy: bulge – Stars: Chemical composition – Microlensing

1. Introduction

Sneden et al. (1995) summarized the new opportunities for stellar population studies with high spectral resolution at very large telescopes. The advent of microlensing helps push these opportunities even further.

The greatest advantage of microlensing is the achromatic magnification of the brightness of the source, allowing the observation of objects that would otherwise be out of reach. The net effect of adding such a lens in front of the telescope is to increase the

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diameter of this telescope. Here we present a specific application of this concept: we have obtained a high resolution spectrum of a magnified ($A \approx 2.7$) bulge main-sequence star at a distance of ~ 8 kpc. This is effectively using the Keck I telescope as a 15m diameter telescope. There is simply no other way to obtain such high resolution spectra of bulge main sequence stars.

While bulge red giants are within reach of the echelle spectrographs of 4m to 10m class telescopes, the bulge main sequence stars demand telescopes with 15m diameter or larger. It is, however, interesting to observe bulge main sequence stars rather than giants for two main reasons. First, for stars near the main sequence turn off it is possible to estimate ages based on accurate photometry and chemical abundances. Unfortunately, the ages of red giants cannot be determined. Second, the atmospheric abundances of some elements are affected by stellar evolution. One such element is lithium, which is depleted due to the onset of convection as the stars evolve up the giant branch (e.g. Spite & Spite 1982, Hobbs & Pilachowski 1988, Boesgaard 1991).

The chemical composition of dwarf stars in the halo and disk components of the Milky Way has been extensively studied because these stars are represented in the Solar neighborhood (Wheeler, Sneden & Truran 1989, Edvarsson et al. 1993). Dwarfs in the bulge have remained beyond reach of existing telescopes because they are intrinsically too faint. The bulge, however, is of particular interest, having high metal (McWilliam & Rich 1994) and He abundance (Minniti 1995). Being at the bottom of the Galactic potential well, it is the place where one expects to find the most chemically evolved populations, formed from gas leftover after the formation of the halo (Minniti 1996). It is our long term goal to take advantage of microlensing in order to assemble a bulge sample like the unevolved F and G disk stars of Edvarsson et al. (1993), and define the chemical composition and enrichment history of the bulge. Such a sample would be invaluable to study the Galactic evolution of lithium (Hobbs & Pilachowski 1988, Lambert et al. 1991, Boesgaard 1991, Balachandran 1995, Spite 1995).

Microlensing will allow for the first time the determination of detailed chemical compositions for bulge main sequence stars *in situ*. Note that this is possible because microlensing is achromatic, and does not affect the stellar spectrum (Benetti et al. 1995) One particular aspect of this program is that it does not need to be a target of opportunity. The MACHO project is producing enough microlensing alerts during the bulge season, that at any given night there are several magnified candidates. However, a disadvantage of microlensing is that the observations are non-repeatable, because the same star is not magnified twice.

2. The Source Star 97BLG45

The star 97BLG45 was alerted on by the MACHO collaboration in late July 1997. Data on the alert was taken from the MACHO Project homepage at **http://wwwmacho.mcmaster.ca**. The position, photometry, and other relevant information are listed in Table 1. The baseline magnitude of this star is listed, although the star was 1 mag brighter at the time of the observations.

The star 97BLG45 is located in the overlap region between MACHO fields 136 and 142, lying at a projected distance of 1.08 kpc from the Galactic center. The position in the MACHO color-magnitude diagram of the bulge (see Alcock et al. 1997a), indicates that this star is likely to be located near the bulge main sequence turn-off. It is too blue to be a disk main sequence star. If it were a disk main sequence star, it would be very distant, and more than one kpc above the Galactic plane, which is unlikely. Also, the location in the color-magnitude diagram is not consistent with this star belonging to the Sgr dwarf.

The reddening in MACHO field 142 has not been measured yet. We estimate the reddening in this field to be $E(V-R) = 0.20$ by extrapolating the reddening measurements of Alcock et al. (1997b). These reddening determinations are based on the mean colors of RR Lyrae in bulge fields. The adopted reddening value implies that 97BLG45 has an absolute magnitude $M_V = +4.4$ if it is located at a distance of about 8 kpc. This places it near the bulge main sequence turn-off.

The observations of 97BLG45 were taken on the first half of the night of August 18, 1997, under sub-arcsecond seeing conditions. We used the Keck I 10m telescope with the HIRES echelle spectrograph (Vogt et al. 1994). The Li I line at λ6707.8 Å is located in the echelle order #22, with a dispersion of 0.094 Å pix^{-1}, yielding a resolution of 0.24 Å, as measured by the FWHM of the spectral lines. The final spectrum consists of the combination of 6 half hour spectra, taken with airmasses ranging from 1.5 to 3. Some of the spectroscopic parameters are listed in Table 2, and a detailed description of the data reduction will be published elsewhere (Minniti et al. 1998). The final combined spectrum of 97BLG45 has resolving power $R = 27000$, and $S/N = 50$ per resolution element. We observed IAU radial velocity standards and abundance standards from the list of Edvarsson et al. (1993). At twilight we also obtained a spectrum of the Sun for comparison, and of rapidly rotating stars. The latter are used for identifying and removing the atmospheric absorption lines. The telluric emission lines are accounted for by the sky present in the columns adjacent to the object for every order. There are no blemishes in the flats, or sky lines next to the Li I 6707.8 line that would affect our measurement of this line. The background sky and scattered light amount to 24 counts per pixel in the mean in this region of the spectrum, or less than 10% of the total counts in this spectrum.

3. The Spectrum of 97BLG45

Figure 1 shows the final combined spectrum of a fraction of the echelle order #22, with the Li I and neighboring Fe I lines indicated. The Li I line shown in Figure 1 is real, judging by the presence of Fe I lines with comparable equivalent width in this region of the spectrum (Table 2). In particular, the equivalent width of the Fe I line at λ6705 Å is similar to that of the Li I line at λ6707.8, justifying our claim of detection of this line.

We measure an accurate radial velocity $V = 89$ km s^{-1} for 97BLG45 by centroiding several strong lines in this region of the spectrum. This radial velocity is consistent with the observed kinematics of the Galactic bulge (Minniti 1996). The observed velocity is too large for a normal disk star, favoring bulge membership, and ruling out membership in the Sgr dwarf ($V = 160$ km s^{-1}).

The star 97BLG45 is single-lined, and has negligible rotation. The rotation was estimated by comparing the FWHM of the strong lines with the emission and absorption lines of the telluric sky spectrum, and with the FWHM of the ThAr comparison lamp lines.

The temperature of 97BLG45 is estimated in different ways: (1) Using the optical photometry, $(V-R)_0 = 0.40$. From the recent calibrations of Clementini et al. (1995), we derive $T_{eff} = 5800$ K. (2) Using the equivalent width of H_α and H_β. This is rather uncertain, because of the difficulties of determining the true continuum for such broad lines. (3) Comparing the line profiles of H_α and H_β with those of the Solar spectrum. This direct comparison reveals that $T_{eff} > T_\odot$.

We adopt $T_{eff} = 6000$K, with an estimated conservative error of $\sigma_{Teff} = 150$ K. The complete spectral analysis will yield another independent value of the stellar temperature (Minniti et al. 1998). The T_{eff} measured for 97BLG45 places it in the Spite plateau (Spite & Spite 1982). Using this temperature, we are able to measure the star lithium abundance, as detailed below.

4. The Lithium Abundance of 97BLG45

The present resolution does not allow the separation of the blend of the Li I resonance doublet at λ6707.76 Å and λ6707.91 Å with the Fe I line at λ6707.41 Å (King et al. 1997). We measure the equivalent width of the Li+Fe blend at λ6707 Å to be $W_{6707} = 58$ mÅ. The error in this measurement is dominated by the choice of the continuum, and we conservatively adopt $\sigma_W = 15$ mÅ. The contamination by the Fe I line at λ6707.4 Å is taken into account following the procedure of Soderblom et al. (1993). We find $W_{Fe6707.4} = 11$

mÅ, yielding $W_{Li6707.8} = 47 \pm 15$ mÅ.

The lithium abundance in 97BLG45 is measured using the tables of Soderblom et al. (1993) and Ryan et al. (1996). We find $A(Li) = 12 + logN(Li)/N(H) = 2.25$, value that is plotted as a large star in Figure 2.

The errors in the lithium abundance are dominated by the errors in effective temperature and in equivalent width. The error $\sigma_W = 15$ mÅ contributes $\sigma_{Li} = 0.2$ dex. The error $\sigma_{Teff} = 150$ K contributes $\sigma_{Li} = 0.15$ dex. We then conclude that $\sigma_{Li} = 0.25$ dex. This error is relatively large compared with other studies because the target star is extremely faint. The detection, however, is comparable to that of Pasquini et al. (1997) in 47 Tuc.

For comparison, Figure 2 also shows the lithium abundances *vs* temperature plane for stars in the Hyades taken from Balachandran (1995), 47Tuc from Pasquini & Molaro (1997), and M67 from Pasquini et al. (1997), along with the Sun. The position of 97BLG45 in Figure 2 is well below the sequence of young open clusters such as the Hyades (with 700 Myr), but it is consistent with older populations such as the open cluster M67 (with 4.7 Gyr), and the old globular cluster 47 Tuc (with 13 Gyr).

The Li I line is stronger than the one in the Solar spectrum. Since the temperatures of these two stars are not very different, the lithium abundance of 97BLG45 is well above the Solar value, as shown in Figure 2. In fact, if the Li I line were as weak as in the Sun, we would not have detected it.

The most recent determination of the primordial lithium abundance plateau from Bonifacio & Molaro (1997), $A(Li) = 2.238 \pm 0.06$, is also plotted in Figure 2 (see also Ryan et al. 1996). The lithium abundance of 97BLG45 is consistent with the mean primordial lithium abundance given by these authors within the errorbars.

While these comparisons are interesting, based on a single measurement we cannot draw any conclusions about the lithium dependence with age and chemical composition in the bulge. The lithium dispersion in the halo stars –Pop II– is very small in comparison with that of the disk stars –Pop I– (Spite & Spite 1982, Lambert et al. 1991, Spite 1995). Clearly, a sample of about 10 objects like 97BLG45 is needed to accurately define the Spite plateau and measure the lithium dispersion in the bulge population. This is currently within reach of the Keck I telescope: for stars magnified by microlensing it would be possible to study the lithium-metallicity dependence (e.g. Lambert et al. 1991), and the lithium-age dependence (Boesgaard 1991) in comparison with the other Galactic components. Such a sample would also allow the measurement of the abundances of different elements in the bulge following the precepts of Edvarsson et al. (1993). Most importantly, it may then be

possible to establish if the bulge formed from gas previously enriched in the halo.

5. Conclusions and Future Prospects

We have introduced a specific application of microlensing as a tool for the study of faint objects, obtaining the first determination of the lithium abundance in the Milky Way bulge: $A(Li) = 2.25 \pm 0.25$. This measurement is based on an echelle spectrum of the microlensing event 97BLG45 of a star near the bulge main sequence turn-off. We have achieved the faintest limit possible with current equipments, using Keck I, the largest existing telescope in the world, with the longest allowed exposure time in the half night, and the bulge main sequence star with highest magnification at the time.

This opens up new possibilities for the study of the chemical composition and enrichment history of the Milky Way bulge, to complement similar studies of the other major galactic components: halo (Wheeler et al. 1989), and disk (Edvarsson et al. 1993). Furthermore, it would not be unreasonable to expect to obtain echelle spectra and measure element abundances in individual stars in nearby galaxies that are magnified by microlensing. Even individual red giants in the M31 bulge, or subgiants in the Magellanic Clouds that are magnified by factors of > 10 would be within reach.

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Table 1. Photometric Data on 97BLG45

Star	MACHO ID	RA_{2000}	DEC_{2000}	l	b	R_{gal}	V	V−R	E_{V-R}	M_V
97BLG45	142.27650.6057	18:21:01.8	–28:46:45	3.943	–6.680	1.08 kpc	19.80	0.60	0.20	+4.4

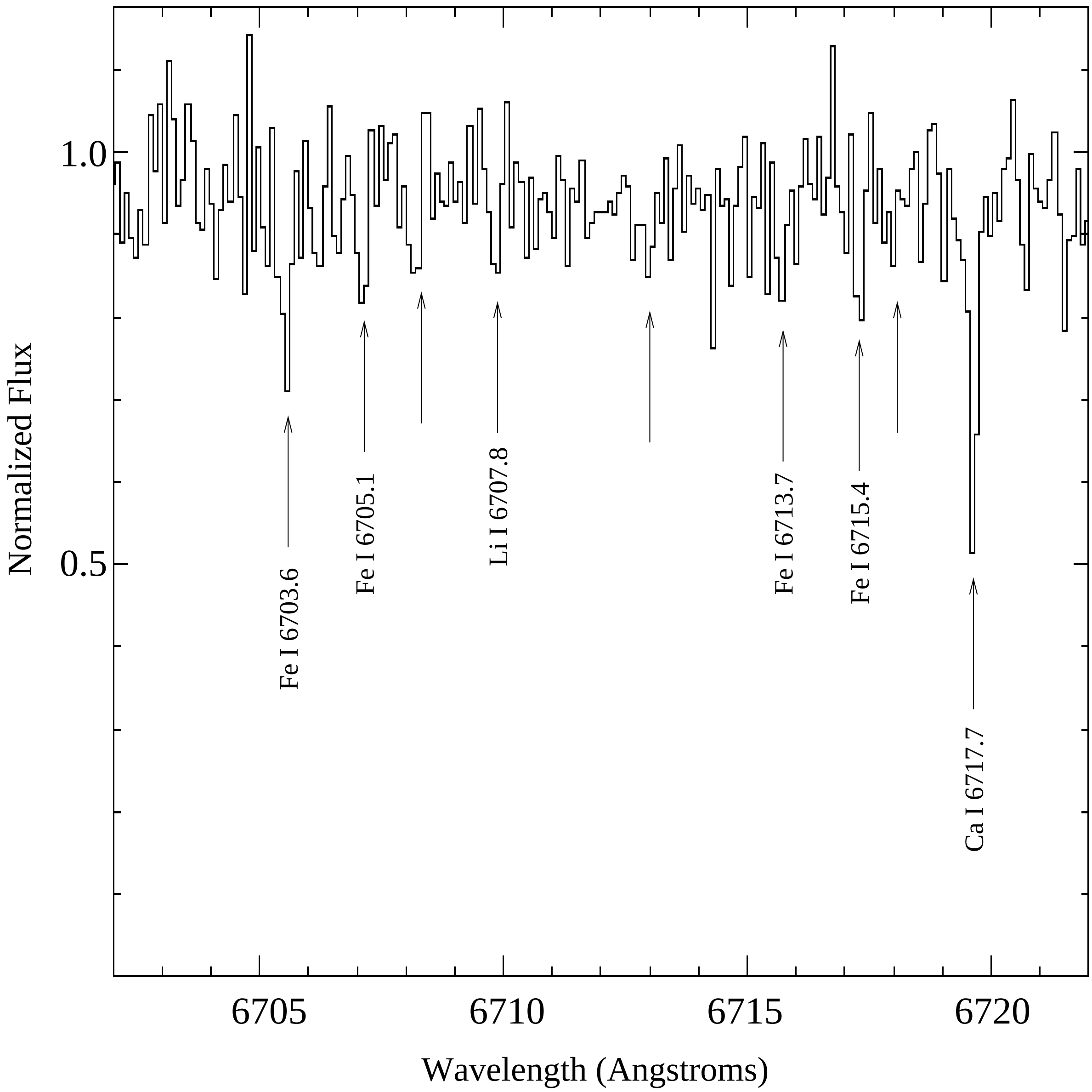

Fig. 1.— Portion of the spectrum with the lithium line. The lines of other elements are also indicated for comparison (blends are not labelled). This spectrum has not been smoothed or binned.

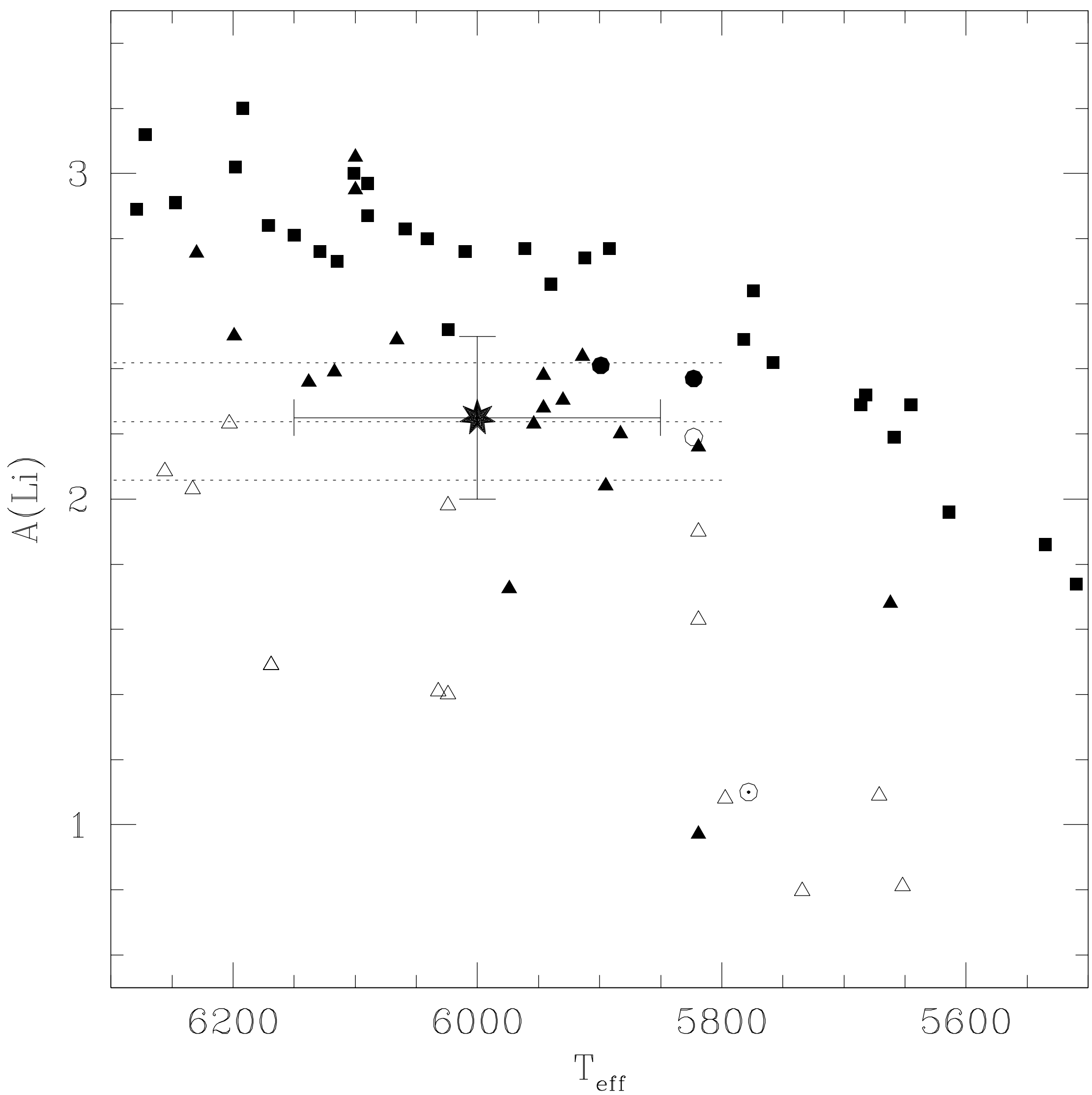

Fig. 2.— Lithium abundances *vs* T_{eff} for the Hyades (squares), 47Tuc (circles), M67 (triangles), the Sun ($\odot$), and 97BLG45 (big star). Full and open symbols indicate detections and upper limits, respectively. The primordial lithium abundance from Bonifacio & Molaro (1997) is shown with the middle dotted line, along with their $\pm 3\sigma$ range given by the upper and lower lines.

Table 2. Spectroscopic Data on 97BLG45

Star	Exptime	Dispersion	S/N	W_{Li6707}	W_{Fe6703}	W_{Fe6705}	W_{Fe6713}	$A(Li)$
97BLG45	6×1800 sec	0.094 Å/pix	50	58 ± 15mÅ	94 ± 15mÅ	64 ± 15mÅ	68 ± 15mÅ	2.25 ± 0.25